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Review of the use of Numerical Weather Prediction (NWP) Models for wind energy assessment

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ABSTRACT

Wind energy resource assessment applications require accurate wind measurements. Most of the published studies used data from existing weather station network operated by meteorological departments. Due to relatively high cost of weather stations the resolution of the weather station network is coarse for wind energy applications. Typically, meteorological departments install weather stations at specific locations such as airports, ports and areas with high density population. Typically, these locations are avoided during wind farms siting. According to WMO regulations, weather stations provide measurements for different weather elements at specific altitudes such as 2 m for air temperature and 10 m for wind measurements. For wind energy resource assessment applications, minimum of one year of wind measurements is required to build wind climatology for a certain site. Therefore data collected from a certain site cannot be used before one year of operation. Due to these limitations, wind energy resource assessment application needs to use data from different sources. Recently, wind assessment studies were conducted using data generated by Numerical Weather Prediction models. This paper reviews the use of the Numerical Weather Prediction data for wind energy resource assessment. It gives a general overview of NWP models and how they overcome the limitations in the classical wind measurements.

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1. Introduction

High quality wind data are an essential source of information during the wind assessment process. Most of the published studies such as [1–6] used data from existing weather station networks operated by meteorological departments. Typically, all meteorological weather stations are equipped with wind speed anemometer and wind vane to measure wind direction. Acceding to World Meteorological Organization WMO [7], wind measurement should be mounted on wind mast at 10 m above the ground.

For wind energy resource assessment applications, minimum amount of wind data should cover a period of one year [8]. Longer periods (10 years) of wind data will provide more reliable results and will identify any long-term variability [9]. The one-year data are usually sufficient to determine diurnal and seasonal variations.

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Even though data from weather stations were widely used in wind energy resource assessment, they have several limitations which require researchers to find alternative source of accurate data.

This paper summarizes the limitations of using data from weather stations for wind energy resource assessment. It also introduces the alternative source of wind data by using Numerical Weather Prediction (NWP) models. Moreover, it reviews the studies conducted based on NWP wind data.

The rest of the paper is organized as follows. Section 2 summarizes the limitation of the existing wind measurements. General overview of NWP and how it overcomes the limitations compared to data collected from weather stations is given in Section 3. Section 4 reviews the wind energy assessment works based in NWP wind data. The uncertainty of wind data derived from NWP is discussed in Section 5. Finally, Section 6 concludes the paper.

2. Wind energy resource assessment using data from weather stations

Due to the availability of wind measurements, researchers used these data for wind energy resource assessment. Studies such as [1–6] used wind measurements for wind energy resource assessment for different countries. Even though, wind measurements from weather stations provided data for wind assessment, these types of data have some constrains which disadvantage their use in the assessment process. These main constrains are as follows:

(a) Wind measurement is costly

Typically, meteorological departments install weather stations with sensors to measure all basic elements such as air temperature, air pressure, humidity, wind speed and direction, visibility and other parameters. Installation of one weather station requires lots of civil work and infrastructure preparation such as electricity and communication lines. In addition, the station equipment including sensors and data logger is relatively costly (i.e. each weather station costs around $130,000).

(b) Coarse resolution of wind measurement

Due to the high cost, many countries run relatively few weather stations compared to the country size. For instance, Oman runs 29 weather stations with a country area of 309,500 km^2 (on average one station for each 8843 km^2). On the other hand, wind phenomenon has very localized features, and hence high-resolution measurements are required for wind energy resource assessment.

(c) Weather stations are intended to serve mainly metrological applications

Besides the technical characteristics, many factors are considered when selecting a site to install a new weather station. Airports and ports have higher priorities because of the required high navigation safety. Besides, higher density population areas are considered before less density population areas. Moreover, the frequency of specific weather phenomena such as convection, fog and sand storms is also considered during site selection. Therefore, more than half of the 29 stations operated by Oman Meteorological Department are installed either in airports, ports or close to urban areas.

On the other hand, wind turbines are typically located at relatively high elevated remote areas to avoid sensitive building such as airports and to avoid high density populated and protected areas.

(d) Wind measurements available at standard levels only

According to WMO recommendation, wind masts are installed at 10 m above the ground. Wind energy applications require wind data at the turbine hub (above 50 m) where few measurements are available at the meteorological departments. Therefore, different extrapolation techniques [10] such as wind shear power law and logarithmic law are used to estimate the wind at higher altitudes. These estimations may introduce significant errors in the wind power resource assessment.

(e) Data accuracy and completeness

Most of the meteorological stations are scattered around the country and data are collected in the main center via different communication means (dial-up, wireless) connections. Unless there is a strict maintenance plan (which is not always the case), missing data from the archiving database is an issue and limits the utilization of the data. Missing data could be due to sensors or communication failures. Moreover, in many countries old weather station data are not fully digitalized and are not made available for researchers, which limit the researchers to use shorter periods of data. To fulfil the accuracy needs, meteorological departments should apply different levels of quality controls on the data before distribution for research studies. Accuracy problems may occur due to lack of proper maintenance and calibration of measurement sensors.

(f) Long period is needed to carry out enough measurement for wind energy resource assessment

For new weather station, a minimum of one-year data is needed before it can be used for wind power assessment. Longer periods (10 years) of wind data will provide more reliable results and will identify any long-term variability. One year of data can represent the seasonal variation on the station site but longer period is needed to represent long-term variation. Therefore, newly added stations to the network cannot be utilized before at least one year of operation.

3. Numerical Weather Prediction (NWP)

NWP model is a computer program that solves the equations describing the atmospheric processes and how the atmosphere changes with time [11].

Vilhelm Bjerknes recognized that NWP was possible in principle in 1904 [12]. He proposed that weather prediction could be seen as essentially an initial value problem. If the initial condition of the atmosphere is known, then the equations of each atmospheric variable can be solved by applying the physical forces that act on them over the time to obtain new values of those variables at a later time.

The principal equations relative to the motion on the atmosphere (called primitive equations) are Newton's second law of motion (momentum conservation), the first law of thermodynamics (energy conservation), continuity equation (mass conservation), equation of state and water conservation equation [13]. Those equations are simplified models of the actual physical processes of the atmosphere. Due to their nonlinearity, analytical solutions are computationally expensive to find and, therefore, a numerical approximation is applied.

3.1. Horizontal and vertical resolution

NWP models divide the atmosphere into 3D cubes as shown in Fig. 1. Grid points are centered in the middle of the cube [11]. NWP solves weather parameter equations for each atmospheric variable at each grid point. The forecasted value represents the grid box area average as shown in Fig. 2.

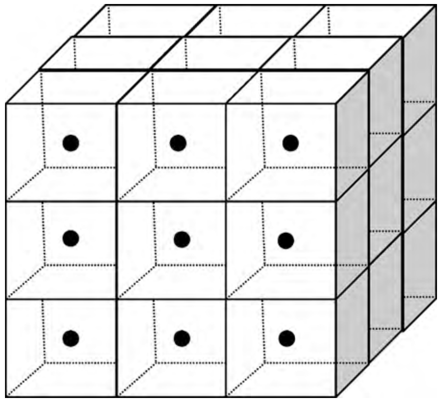

Fig. 1. 3D cubes of the atmosphere used by NWP models.

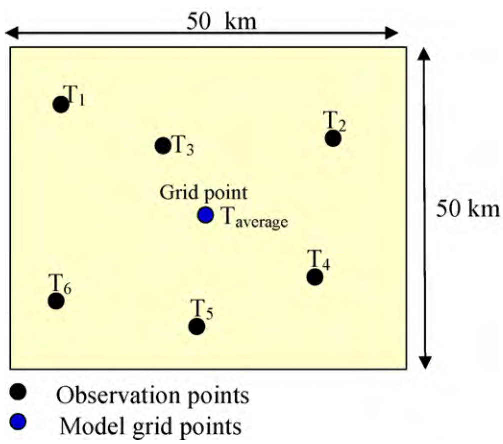

Fig. 2. 50 km grid box, represents area of 2500 km^2.

The minimum distance between adjacent grid points represents the horizontal model resolution. Higher resolution (more and closer grid points) models are more accurate than lower resolution models [12]. On the other hand, they need more powerful and faster computers to run. If the horizontal resolution is halved, then the number of grid points for the same domain is increasing by a factor of 4.

Model resolution has a direct effect on the terrain orography representation on the model [12]. Orography representation is limited to the availability of the high-resolution terrain dataset. If the terrain dataset is coarse, it cannot provide details about the orography to high-resolution models. Due to the grid point averaging, elevations of the highest mountain peaks are generally less than what they are in reality and valleys are often not represented or are represented with less elevation difference between peaks and valley floors. This implies that orographical influence features such as convection and downslope wind will not be fully depicted by the model. Fig. 3 shows how Hajar Mountains in Oman are represented by 28, 7 and 2.8 km resolution. From the figure, it can be seen that 7 km resolution shows more details than the 28 km resolution with mountain peak around 2200 m. The 2.8 km resolution shows smoother features with mountain peak of 2400 m. However, it was not able to depict the actual mountain peak of around 3000 m.

NWP models divide the atmosphere vertically into layers to depict the weather phenomena. The higher number of vertical layers, the better chance to depict the weather phenomena but also more computational power is needed [11].

Many NWP models divide the atmosphere into unequally spaced layers. More layers are generated in the lower part of the atmosphere where most of the weather phenomena accurse [12]. Increasing the vertical resolution in the lower atmosphere enables the models to better define boundary layer processes and features that contribute significantly to sensible weather elements, such as low level winds, turbulence, temperature, and stability. Many NWP models use hybrid vertical coordinate systems such as sigma-pressure where it follows the terrain on the lower part of the atmosphere and follows pressure levels on the upper part of the atmosphere as shown in Fig. 4.

For numerical stabilization, NWP models are not allowed to calculate large change in the atmosphere state during one time step; therefore, small time steeping is used. For example, if the time step is 100 s, to calculate 24 h forecast, the NWP models will calculate the atmospheric state at 0, 100, 200 s until it reaches 86,400 s ($24 \times 60 \times 60$) [12]. Higher resolution models required smaller time steps and hence more computational power.

3.2. Domain coverage

Based on the domain coverage, NWP models are divided into global models and limited area models (LAM). Global models solve the primitive equations for the whole globe while limited area models cover only limited domain. Because of the limitation in computational resources, few meteorological centers run global models and typically are using coarse resolutions. German meteorological center runs a global model (GME) with 40 km horizontal resolution and 40 vertical layers [14]. National Center for Environmental Prediction NCEP/NCAR also runs a global model with 40 km resolution [15]. On the other hand, and due to the availability of powerful super computers, European Centre for Medium-Range Weather Forecasts (ECMWF) is running an operational global model with 25 km resolution [16]. Because of their low resolution, global models cannot detect small scale phenomena such as orographical induced convection [12].

Recently, many meteorological departments started running limited area models (LAMs) to cover the domain of the country and the surrounding areas. LAMs can run using small to medium computers and can run in high resolution (less than 10 km). Compared to global models and due to their high resolution, LAMs are typically used to forecast mesoscale weather phenomena [11]. On the other hand, and due to the limited area coverage, LAMs need boundary conditions from global models. Different LAMs are available for research and operational use. They typically differ in term of numerical formulation, assumptions and equation simplifications. High-resolution model HRM [17,18], ETA [19,20], mesoscale model MM5 [21,22], Weather Research Forecast WRF [23,24], ALADIN [25] and Consortium for Small scale Modeling COSMO [26,27] are examples of limited area models.

One of the main assumptions which differentiate between models is the hydrostatic assumption. Hydrostatic models, assumes a balance between the weight of the atmosphere and the vertical pressure gradient force [11]. This means that no vertical accelerations are calculated explicitly. The hydrostatic assumption is valid for synoptic- and planetary-scale systems and for some mesoscale phenomena. A most notable exception is deep convection. Nonhydrostatic models include an additional forecast equation that accounts for vertical accelerations and vertical motions directly [12]. This additional equations will result in a longer processing time or in an increase in the required computational power.

3.3. NWP models as alternative source of wind data

Typically, meteorological departments run their operational NWP models twice a day to provide the forecasters with guidance

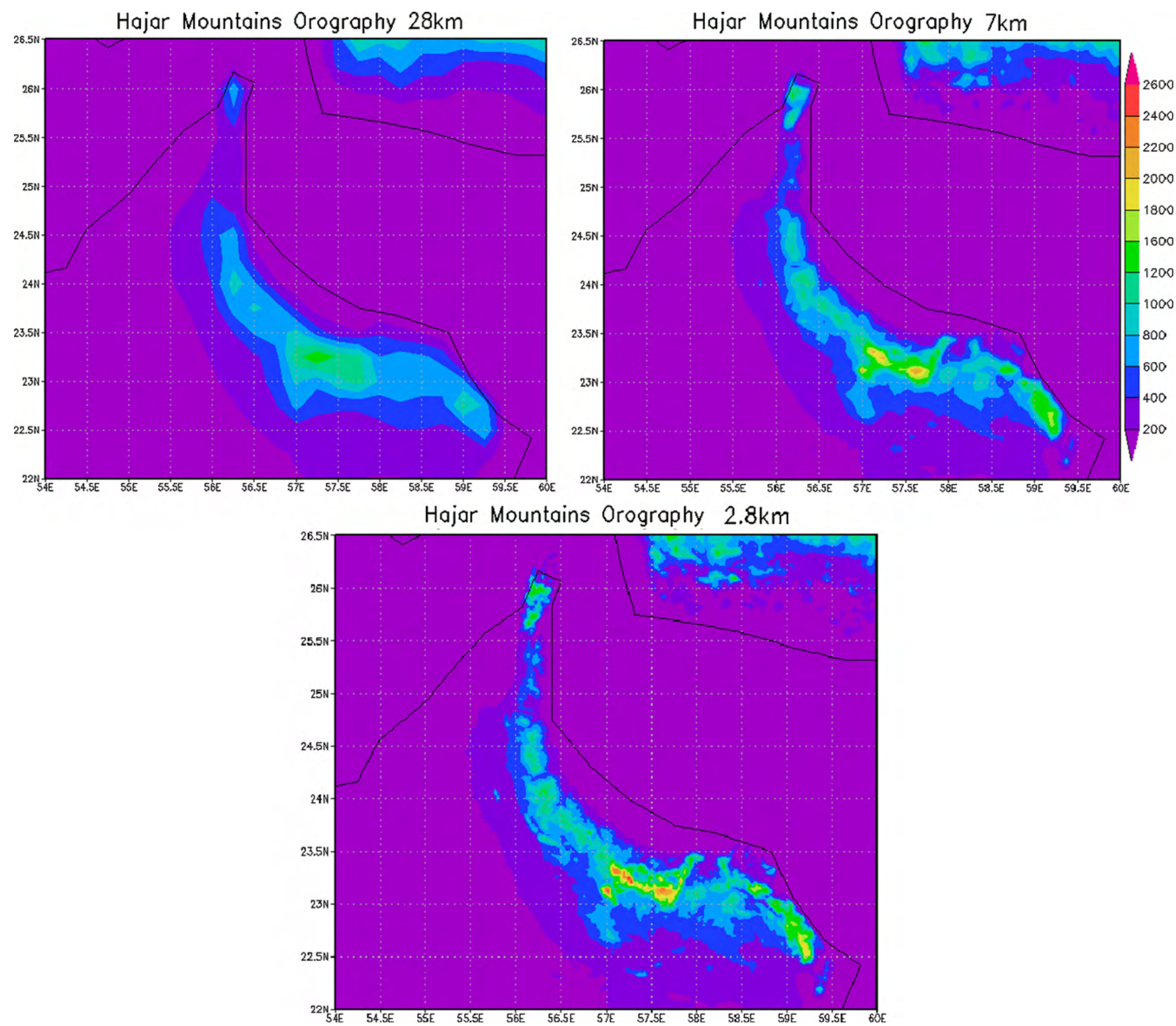

Fig. 3. Hajar Mountains orography (m) using 28, 7 and 2.8 km resolution.

for different parameters. For short-range forecast, three-day forecast is generated each run with hourly forecast output. Wind speed and direction are typical model output parameters. Therefore, wind data from the model output can be used in the wind energy resource assessment. NWP models overcome the constrains of wind measurements in wind energy resource assessment. The following sections explain how NWP models overcome these constrains described in Section 2.

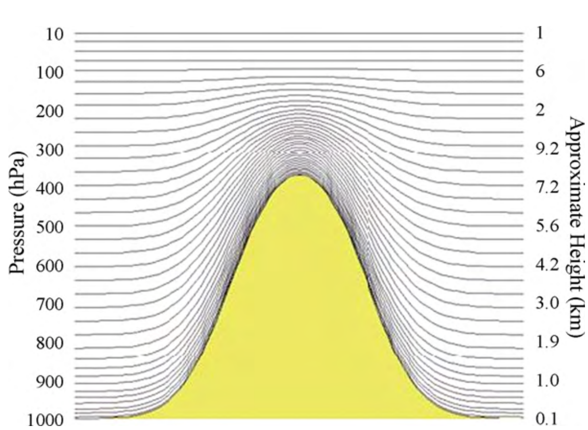

Fig. 4. Hybrid sigma-pressure vertical coordinate system.

1- *Cost issue*: Today, many NWP models are freely available for download from the Internet such as Weather Research Forecast WRF, ETA and MM5 model. Some of them require written agreement between the developers and the user (meteorological departments or researchers) such as the HRM and ALADIN. On the other hand, some of the NWP models are freely available for research such as the COSMO model. For research purposes, the only cost involved is the cost of the processing computers. Nowadays, many meteorological departments and researchers use distributed memory computers (PC Cluster) to run their limited area models. PC clusters provide relatively cheap, reliable, scalable and powerful computers. Moreover, they provide the ability of using the existing office desktop with high speed interconnection network to provide the required computational power.
2- *Resolution issue*: NWP models can run in very high resolution. Operationally 2–3 km resolution model exists for small domains. The availability of computational power is the main constrain in running high-resolution models.

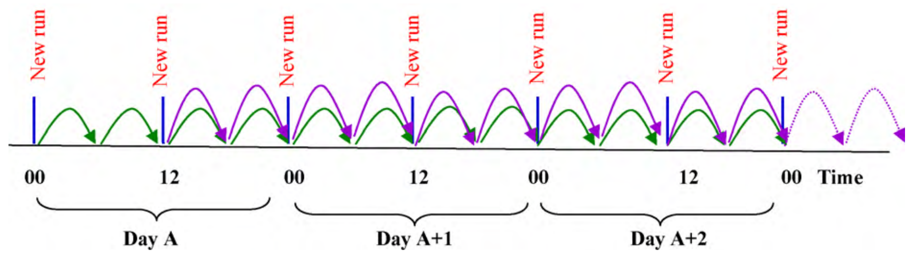

Fig. 5. NWP model run time line.

3- *Interpolation issue*: NWP models provide gridded data for the whole model domain. If the model resolution is 2 km, then the forecast value is given by the model for every 2 km. Therefore, data are not limited to the weather station location; hence, remote locations with no wind measurement can be investigated. Unlike interpolated gridded data, NWP models solve an explicit equation for each grid point which minimizes the approximation errors.
4- *Upper level wind data*: NWP does not provide wind values at 10 m only but also at higher altitudes. NWP models solve the weather element equations for each vertical layer of the atmosphere. Vertical layers are typically configurable input parameter for the model. Layers at different altitudes can be selected to investigate the wind potential energy.
5- *Missing data issue*: Unlike real world measurement where we cannot go back in time, NWP models provide flexibility to go back and forward in time. NWP models can be rerun for any historical event or period of time. For LAM, the only needed input is the boundary condition from the global model. The availability of the boundary condition determines the length of forecast that NWP model can perform. If three days boundary conditions are available then LAM can forecast up to three days. The forecast quality declines with time length. LAMs are typically initialized every 12 h and from the initial time they perform 72 h forecast as shown in Fig. 5. Assuming the time in Fig. 5 is UTC, if the model was initialized at 00 UTC of Day-A, it will give an hourly forecast (green arrows) until 00 UTC of Day-A + 3. At 12 UTC of Day-A, a new run is initialized and performs 3 days forecast until time 12 UTC of Day-A + 3 (pink arrow). (For interpretation of the references to color in this sentence, the reader is referred to the web version of the article.) In case and for some reasons, if one initialization of the model was not able to start, citrine hour in future can be reached using the other available model runs. For example, the 12 UTC of Day-A + 1 can be reached from four different forecasts. First forecast is the 36 h forecast from 00 UTC of Day-A. It can also be reached by 24 h forecast from 12 UTC run of Day-A. Moreover, it can be reached by 12 h forecast from 00 UTC run of Day-A + 1 and finally from 0 h forecast (called model analysis) of 12 UTC run of Day-A + 1.
6- *Climatology period*: Unlike real world measurements where it is required to wait one year to collect one-year data, depending on the computational power, NWP models can provide one year of data within shorter period of time. This saves researchers time, money and effort.
7- *NWP does not ignore measurements*: Weather prediction is an initial value problem; therefore NWP model needs to know the initial state of the atmosphere to predict the future. Initial state of the atmosphere is constructed by a process called Data Assimilation using real world measurements and the previous short-range model output [28]. An initial value for each grid point is required to start the NWP model. Therefore, different types of measurements are considered including surface observations, upper air observations, vertical wind profilers, remote sensing satellite data and measurement taken by airplanes during the takeoff and landing. Fig. 6 summarizes the main components and processes involved in NWP model.

From Fig. 6, it can be seen that the NWP model (yellow rectangle) consists of dynamical processes (atmospheric processes such as advection, pressure gradient forces, and adiabatic heating and cooling) and physical processes (processes operating on scale lower than model resolution including cloud and precipitation micro-physics). Numerical processes represent how the dynamic and the physics will be handled. Numerical processes include model formulation, resolution, domain and data handling. Data assimilation is the process through which real world observations are incorporated into the model initial fields.

Different observation sources including surface, upper air, satellite and airplane are passed to the quality control system and then to the NWP model. Data assimilation process creates the initial state of the atmosphere using the latest observation and the last short-range model forecast and then the model starts the forecast process. For the model to know the weather condition outside its domain that may affect the atmosphere inside its domain, it requires lateral boundary conditions from the global model.

The forecast output of the model is then sent to the post-processing which may include the direct use of the model output or applying some statistical correction or other numerical processing such as downscaling.

Possessed output can then be used for weather forecasting, or to initialize other models such as wave models. They can be also used

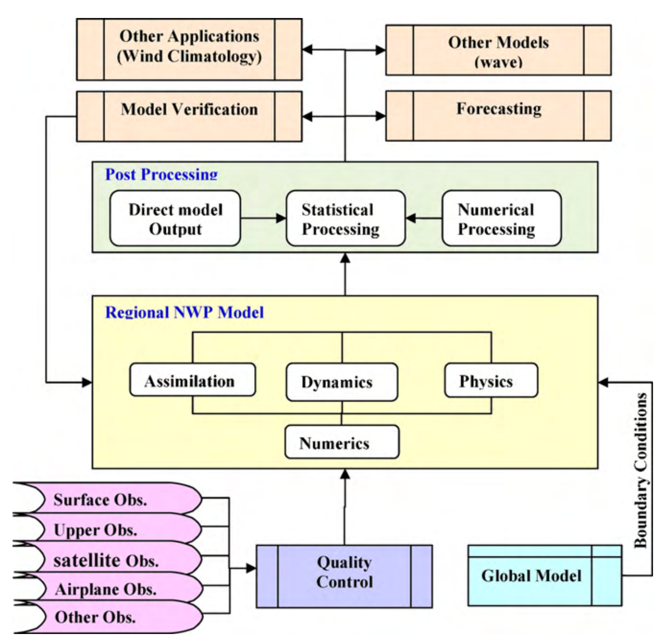

Fig. 6. NWP model Processes data flow (adapted from [12]).

for other applications such as wind power prediction and building wind climatology. Model output cannot be used without verification with what happens in reality (observations). The model verification results are then used to improve the quality of the model.

4. Wind energy resource assessment studies based on NWP wind data

Recently, many wind assessment studies were conducted using NWP model wind data. Different NWP models such as WRF, MM5, COSMO and RAMS were used by different researchers. Depending on the available computational power, different horizontal resolution and vertical layers were used.

In [29], comparative study was carried out for wind assessment using WApS and the mesoscale model MM5 for the German Bight. Wind data were generated for 2004 with 9 km resolution. MM5 runs using NCEP data with 24 vertical levels. The verification results showed that MM5 underestimated the offshore wind by approximately 4% at 10 m above the ground. MM5 showed good agreement with the measurement at low heights 30 and 40 m but the increase of wind speed with height was underestimated with 4% difference at 100 m height.

In [30], verification results for using mesoscale model during wind resource assessment were presented. WRF model was used to derive wind data using 6 and 3 km resolution and 42 vertical layers. NCEP reanalysis data were used as initial and lateral boundary conditions. WRF was initialized four times a day at 00, 06, 12 and 18 UTC. The verification results showed that model simulation winds are generally weaker than the measured data by about 5%.

Study on the ability of mesoscale model to reproduce wind data for offshore wind resource assessment was investigated in [31]. Mesoscale models MM5 and WRF were used with 4.5 and 1.5 km resolutions to reproduce wind for 2005 over Japan. Japan Meteorological Agency Mesoscale Analysis JMA-MANAL model with 10 km resolution was sued to provide the needed initial and lateral boundary files. Offshore data and wind profile data were used to evaluate the accuracy of both models. The study showed that both MM5 and WRF reproduced the wind data better than JMA-MANAL with monthly bias between 0.24 and 1.9 m/s. The wind verification of the higher altitudes showed better scores than the surface wind scores and hence the lower scores were referred to the planetary boundary layer PBL and surface processes model scheme.

In his PhD thesis [32], Paul Nolan studied the effect of climate change on wind energy resources of Ireland. Two regional climate models namely RCA3 and COSMO model were used. RCA3 is purely climate model while COSMO model can run at both climate and prediction modes. ECMWF data were used to initialize both models. COSMO model was used to predict the wind data for 2005 and 2006 using 7 and 2.8 km resolutions with 45 vertical levels. It was concluded that COSMO model gives more fit to observations than ECMWF analysis data. It was also concluded that the 2.8 km resolution did not show an overall substantial improvement over the 7 km resolution except for specific locations and hence to save computational time 7 km resolution simulations were carried out for the climate change study.

Wind potential energy of Tokyo (Japan) was investigated in [33] using NWP model. They used the non-hydrostatic Regional Atmosphere Modeling System (RAMS) model to run 8 and 2 km resolutions simulations over the supply area of Tokyo. Due to the computational limitations they split the computational area into two sub-regions. The verification of model data showed good agreement with the measurements data from Choshi stations with prediction error of the annual mean wind speed of 4.8%. Areas with fishermen rights were eliminated using Geographical Information System GIS. Different scenarios using bottom mounted foundation turbines and floating foundation turbines were investigated.

In [34], the work carried out to generate wind atlas for Egypt was presented. Reanalysis data from NCEP/NCAR were used to generate the NWP wind climatology. These data were downscaled to 7.5 km resolution using the statistical–dynamical downscaling model of Karlsruhe Atmospheric Mesoscale Model KAMM. The simulation results were used to generate wind resource maps at different levels above the ground. The verification results of comparing the wind data measurements and the derived wind data from NWP model showed good agreements in some locations and poor agreement in other locations. The poor agreement was referred to the coarse resolution of NCEP global data, the complex topography over Gulf of Suez and the roughness length values used during the study.

Wind resource map for Spain using Skiron mesoscale model was presented in [35]. NCEP ($1^\circ \times 1^\circ$) global model data were used to provide initial and boundary condition to Skiron. Data for 2006 were derived for west Mediterranean Sea, southeast Europe, Northeast Africa and East Atlantic using 11 km resolution. Kiron was initialized using the 00 UTC data to generate 72 h forecast. From each model run, data from 13 to 36 h forecast were considered while the first 12 h were discarded due to the spin-up of the model. The verification results showed wind speed annual bias of 1.87 m/s over what they call simple complex terrain and annual bias of 2.5 m/s over complex terrain. These bias values were referred to the coarse resolution of Skiron.

5. Uncertainty of wind data derived from NWP

National weather services enrol high-resolution NWP models to meet the growing demand of the public for accurate and detailed weather forecasts [36]. NWP model outputs are used for weather forecasting and as input for other applications such as air pollution and hydrological forecast.

From the studies discussed in the previous section, it is clear that wind data derived from NWP model were biased. Most of the studies showed an underestimation of about 5% of the wind speed especially close to the surface. Therefore, with the increase of the NWP model output usage in wind energy resource assessment, it should be clear that NWP models have limitations [12] due to the following:

(a) *Model formulation*: NWP model is by definition an approximation of reality [11]. Therefore model structure such as horizontal resolution, vertical resolution and time integration procedure may contribute in the uncertainty of the NWP model output.
(b) *Simplifications in physics*: Atmospheric physical processes such as solar radiation, turbulence and convection are simplified in the NWP models due to the limitation in available computational power. Moreover, many other physical processes cannot be explicitly modeled because they are not sufficiently understood to be represented in equation format or there are no appropriate data to represent them [12].
(c) *Uncertainty in the initial state*: observational data are collected and then processed to generate the initial state of the atmosphere before NWP model starts. Due to the spatial resolution and temporal frequency of the observation, uncertainty in the initial state may occur. Moreover, the uncertainty may occur due to instrumentation errors or missing data. It may also appear in the quality control process or data assimilation process [28].
(d) Uncertainty in lateral boundary conditions: high-resolution limited area models require information at the edge of the model domain. These boundary data are meteorological conditions represented mathematically. Typically, LAM relies on coarse resolution global model to provide lateral boundary conditions. The quality of the boundary condition data influences the quality

of the LAM output. Consequently, use of any mesoscale LAM should start with validation of the synoptic forecast (global model) used for the LAM domain boundaries [28].

(e) *Uncertainties in surface characteristics*: Vegetation type, soil type and vegetation fraction are required by NWP models to emulate vegetation effects on surface processes such as evapotranspiration, surface fluxes due to short wave and long wave radiation [12]. This information has direct effects on surface and boundary-layer temperatures, moisture, and other forecast variables. Due to computational constrains, operational NWP models, group vegetation and soil types in more general categories and assign them similar characteristics such as evaporability factor, surface roughness and albedo. These assumptions have significant implications for surface conditions in the model forecasts and contribute to the model output uncertainty. Depending on the application, post-processing calculation can be then applied to introduce the orographical effects using mass consistent models [37] such as WAPs application for wind energy applications [9]. These models contain no time derivative and the values are adjusted to satisfy the laws of mass conservation caused by the topographical forcing.

6. Conclusion

Wind energy resource assessment applications require highly accurate wind data. Classically, wind data were collected from weather station networks operated by meteorological departments. These types of data have some constrains such as relatively high operating cost, coarse resolution, and representativity and availability problems. Due to these constrains wind data from NWP models can be considered as alternative source of wind data.

An overview of the NWP models was given. The superiority of NWP wind data over the classical wind measurements was also explained. In addition, an overview of the recent studies in wind assessment using NWP wind data was presented. Since NWP models are just an approximation of the reality, the source of uncertainties in the NWP model output was also described. This source of uncertainties is well represented by wind speed bias of around 0.25 over flat terrain and 2.5 over complex terrain as shown in the surveyed studies.

Different statistical approached are nowadays used to correct the bias in the direct model output such as Model Output Statistics MOS and Kalman filter. Improvement of the model physics and dynamics may lead to better verification scores. In addition, improvement in data assimilation algorithms is also another approach to be tested. Finally, with the increase of available computational power, many meteorological departments are introducing regional ensemble forecast to improve the quality of their forecast.

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